U.S. Navy Journal of Underwater Acoustics Volume 25, November 4 October 1975

HISTORICAL REVIEW OF UNDERWATER ACOUSTIC TECHNOLOGY: 1939–1945 WITH EMPHASIS ON UNDERSEA WARFARE

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(Received 9 April 1975)

ABSTRACT

This article presents selected technical accomplishments of the undersea warfare program organized by the National Defense Research Committee (NDRC) during World War II. These accomplishments developed the basis of the present day science of underwater acoustics as well as the first cohesive systems approach to both anti- and prosubmarine warfare.

INTRODUCTION

The mobilization of more than 32,000 scientists and engineers during the second World War under the Office of Science and Technology (OSRD) and its sub-organization, the National Defense Research Committee (NDRC), was described in a previous article.[1] Out of this mobilization came improved radar, sonar, communication gear, the proximity fuse, and weapon systems of all kinds, including the ultimate weapon system, the atomic bomb.

One part of NDRC, Division 6, "Undersea Warfare," employed more than 2,500 scientists and engineers by the end of the war. Stressed was the need for rapid research and development, the transfer of R&D efficiently into fleet equipment and techniques, and assistance to fleet operations to assure that available capability was best used.

Figure 1 summarizes the organizational interrelationships between the Navy and the OSRD/NDRC for the conduct and coordination of undersea warfare. The main channel between the organizations was the Coordinator of Research and Development in the Navy that, on one hand, passed the needs of the Bureaus to Division 6 and, on the other, transferred Division 6 solutions back into the Naval system to produce appropriate operational gear for fleet use. After the war, this office became part of the Office of Naval Research. Operating directly with the fleet were the Anti-Submarine Warfare Operations Research Group (ASWORG) and the Field Engineering Group (FEG), that assisted Navy Bureaus in checking and modifying equipment at Navy yards and advanced bases. Also shown in Fig. 1 are various Bureau Laboratories and the Division 6 Laboratories that engaged in underwater acoustic activity. Table I describes the R&D areas investigated. Most of the research and development activity was under NDRC management and control. (The details of organization were delineated in Ref. 1.)

Selected technical accomplishments in the areas of sonar and silencing, first in antisubmarine and then in prosubmarine warfare will be presented with appropriate historical background. The omission of sound propagation investigations is considered justified on the basis of extensive previous reporting in the literature.

[1] M. Lasky, "Review of Scientific Effort for Undersea Warfare: 1939–1945," *JUA (USN)* 25, 567-584 (1975).

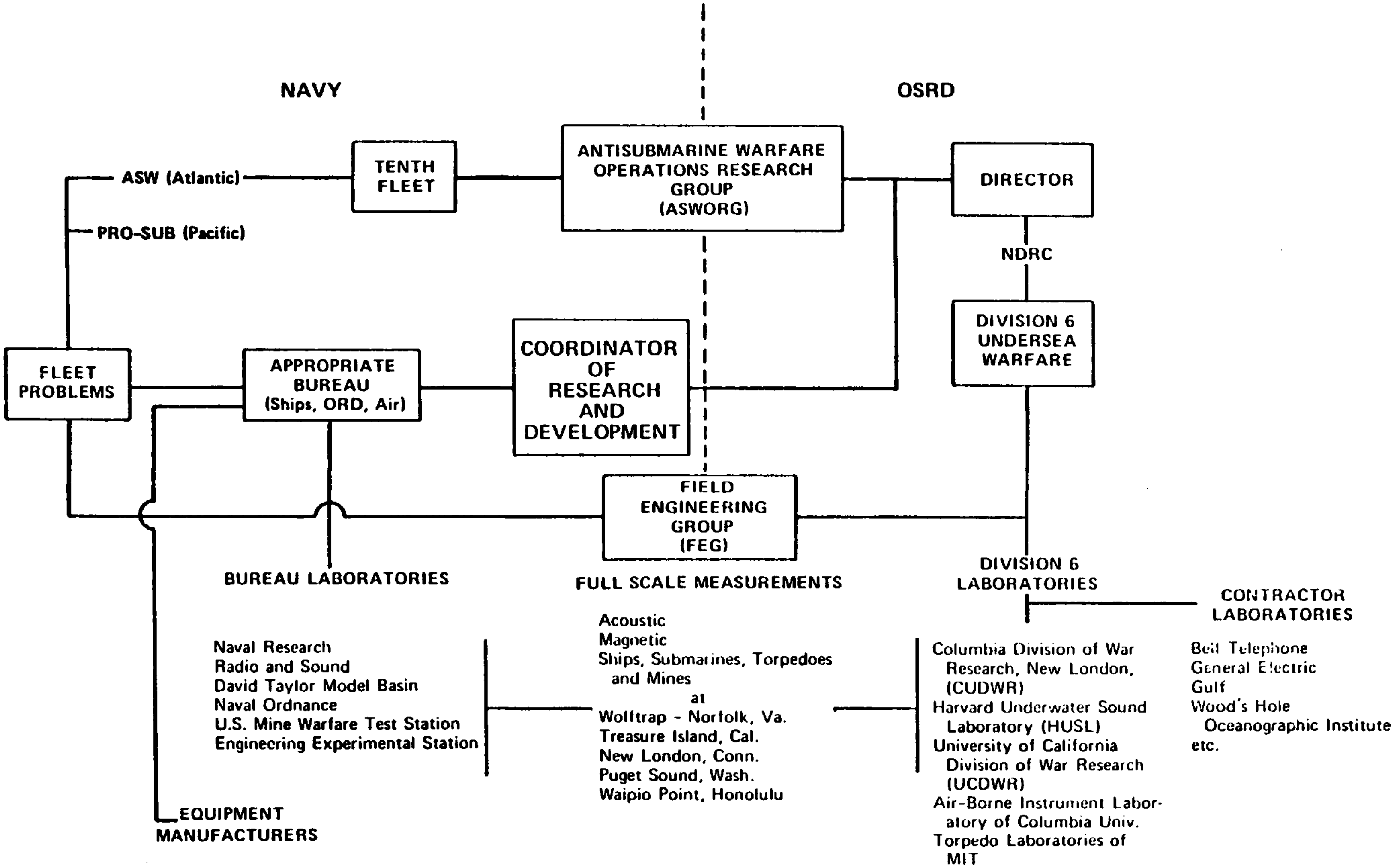


Fig. 1. OSRD/NDRC—Navy organization for the conduct of undersea warfare during World War II– 1942-1945

TABLE I
Areas of Investigation

Improvement Fleet Capability	Accelerated Research and Development	
	Research	Development
Better sonar Improved weapons Improved operator training Improved use of resources Operational analysis (tactics) Field engineering (installation and maintenance)	Standards Measurement & analysis technology Hearing & target detection & recognition Source, medium, receiver investigations	Active sonar Passive sonar Sonar countermeasures Special devices • Training • Mine location • Self-noise monitoring • Air-towed, etc.

(Source—Author's Summary NDRC, Div. 6, Vol. 1, Subsurface Warfare (1946))

BACKGROUND

Between the two world wars, the United States and Great Britain went their separate ways in developing underwater acoustic equipment for naval warfare application.[2,3] In the United States, the Naval Research Laboratory and, in Britain, the Admiralty Research Laboratory developed equipments and techniques under the strict cloak of security regulations. Information was not exchanged until early 1940. By then it became apparent that our respective developments were parallel and that both stressed the improvement of echo-location equipment first discovered at the end of World War I. Expenditures were limited in both nations due to the great depression. As late as 1936, the overall Naval Research Laboratory Sound Division consisted of a total of only 11 scientists and technicians. John Herrick described the situation as such: "Prior to the war, the underwater sound program was starved for funds. Scientists had to be imbued with both patience and patriotism to put up with the Civil Service Scale allowed for the first rate talent. But the Navy Department, Bureau of Engineering, which in 1941 became part of the Bureau of Ships, went energetically, if slowly, ahead.[4]"

An information exchange between the United States and the United Kingdom started in September 1940 and eventually included all aspects of undersea warfare. At the beginning of the war, in the early days of scientific interchange, there is no question that American received more than it gave. It was not until 1942 that NDRC produced important results, first in ASW and later in prosubmarine warfare.

During the interval of 1940 to 1941, a blue-ribbon panel, headed by Dr. I. Colpitts of the Bell Telephone Laboratories, reviewed the naval capability to conduct warfare under the sea.[5] In view of the U-boat threat in the Atlantic, antisubmarine capability was emphasized; to a lesser degree prosubmarine capability was also assessed. Some of the report highlights are as follows:

- Acoustic measurements of all kinds were needed so that the warfare problems involving men, equipment, and sound transmission could be dealt with in an organized and scientific manner. In view of the advances that had been made in improving techniques for air acoustic measurement, an extension of technology was needed in the area of underwater sound.

[2]M. Lasky, "A Historical Review of Underwater Acoustic Technology with Emphasis on Undersea Warfare," 1916-1939, *JUA(USN)* 24, 597-623 (1974).
[3]E. Klein, "Notes on Underwater Sound Research and Applications Before 1939," ONR Report ACR-135 (Sept. 1957).
[4]J. Herrick, "Subsurface Warfare, the History of Division 6, NDRC," The Department of Defense, "Research and Development Board," Washington, D.C. (Jan. 1951), p. 7
[5]J. Herrick, Op. Cit., pp. 12-14 and appendix.

• The antisubmarine echo-location equipment, developed by NRL in the mid-1930's for the peacetime Navy, had grave deficiencies. Improvements were needed to simplify operations and to train operators. In addition, the cumbersome techniques for guiding the delivery attack of explosives to within 30 ft of the U-boat hull, the lethal radius of the depth charge, had to be improved greatly. *The sensor-explosive delivery problem had to be undertaken as a system. (In the Navy, the Bureau of Ships managed the sound gear while the Bureau of Ordinance was responsible for the depth charges.)*

• The capability of ASW air platforms (aircraft and blimps) to find and attack submarines operating on the surface was in the process of being improved by radar installation; therefore, sensors were needed to allow the continuance of attack once the target submerged. The possibilities of magnetic detection from aircraft needed to be investigated.

• The prosubmarine passive listening systems installed on fleet submarines needed conversion from ultrasonic to sonic listening. The system in use heterodyned signals in the high frequency range to audio frequency. Although suitable against cavitating-screw targets, it could not easily detect enemy ASW vessels operating at low speed. For the protection of our own submarines, an improved sonic-listening passive system was urgently needed.

Colpitts presented the report recommendations to the General Board of the Navy in March 1941. Jewett and Bush were called in to join the proceedings and were formally requested to have the NDRC implement the report recommendations. Shortly afterwards the NDRC recources were expanded tenfold under OSRD. Division 6, Undersea Warfare was organized with the resources to correct the identified deficiencies.

ANTISUBMARINE RESEARCH AND DEVELOPMENT

Emergence of the Multidiscipline Science of Underwater Acoustics

Three main laboratories concerned with undersea acoustics were organized by the Undersea Warfare Division of NDRC. These included the Harvard and Columbia Laboratories at Cambridge and New London, respectively, to deal with short-term equipment improvement (especially to localize U-boats) and the University of California, San Diego Laboratory to develop needed longer term studies, especially on sound propagation through the sea. In addition, the New London and San Diego laboratories were assigned the responsibility of assisting the Navy with the selection and training of sound operators. To accomplish the wide variety of tasks many scientific disciplines were enlisted. Included were large numbers of physicists, electrical and electronic engineers, as well as many psychologists, oceanographers, marine biologists, mathematicians, actuaries, chemists, structural and hydro-mechanicists. The combination of all this talent to work on the totality of the problem was a unique development.

The habit of all scientists is to measure quantitatively all aspects of a given phenomenon. The scientists in the program proceeded to do so. All aspects of the Navy's endeavors with sound in the sea was subjected to quantization. All of the sonar parameters, all that we now term the "Sonar Equation," was measured repeatedly, and with improved skill as time went on. With priority funding, a huge amount of technology and information was produced in three and a half years. As Urick described the effort and its results, "Indeed in retrospect there is little of our fund of underwater acoustic knowledge that cannot be traced in its rudiments to the discoveries of the wartime period.[6]" Impelled by the wartime needs, underwater acoustics emerged as a newly created, Navy associated, multidiscipline science. (At the end of the war, the findings of that part of NDRC engaged in underwater acoustics for Naval Application were summarized in an admirable series of 22 reports, the NDRC Division 6 Summary Technical Reports.)

[6]R.J. Urick, *Principles of Underwater Sound for Engineers* (McGraw-Hill, New York, 1967), pp. 2, 3.

Emergence of the Science of Operations Research

Dr. James B. Conant visited England during the Battle for Britain and returned convinced that one of the main factors that saved Britain from destruction by the Luftwaffe was a group of civilian scientists who worked next to and assisted Royal Air Force operations officers. They worked together on the problem of using the early-warning coastal radar net to optimally deploy the limited number of defending aircraft. Professor M. S. Blackett was prominent in this group. In a paper entitled "Scientists at the Operational Level," he wrote: "Relatively too much scientific effort has been given to the *production* of new scientific devices and too little in the *proper use* of what we have got." Scientific methods of analysis were needed, "especially in those aspects of operations into which probability considerations and the theory of errors enter." After the Battle of Britain decreased in intensity, the British extended the use of this "Operations Research" to ASW.[7]

After Bush moved up to Director of OSRD, Conant became Chairman of NDRC and negotiated with the Navy to copy the British example. In March 1942, the Navy requested that Division 6 supply operations research assistance to the Antisubmarine Warfare Unit, Atlantic Fleet. The Antisubmarine Warfare Operations Research Group (ASWORG) was established with Dr. Philip Morse of the Massachusetts Institute of Technology in charge and moved to work directly with the officer personnel at Navy ASW Operational Headquarters. From then on throughout the war, ASWORG worked closely with the Fleet. In an area of little past precedence or practice, the group took hold and, moreover, built a new science applicable to naval operations. In addition, the Group introduced a "two-way" liaison between the Fleet and the technical community. By being able to translate the "tribal" language of each, ASWORG improved the communication between the operators and those who provided them their tools for warfare. Improved and rapid communication was essential to save time in the development of needed equipment modifications.[8]

Measure-Countermeasure Acoustic Warfare, 1942[9]

In the grim days of Spring 1942, we were losing the Battle of the Atlantic with U-boats sinking up to 143 ships a month, faster than we could replace them. Our success rate in sinking U-boats was less than 5 percent per submerged attack operation; that is, for more than 20 attacks we would achieve 1 kill. ASWORG and their opposite numbers in Britain gathered all available information and began to find operational answers. It became apparent that at critical moments sound gear lost contact because the U-boats, hearing the pings grow louder, correctly judged the moment of attack and immediately submerged deeper and maneuvered into a sharp turn to get away. In this action they also emitted bubble-making chemicals to send back false echoes to the searching gear. To counter these tactics, a creeping attack was devised whereby one destroyer using echo-ranging brought a second destroyer over the target by radio signals. In addition, suitable training was devised to enable sound operators to learn to distinguish fixed from moving targets by concentrating on the Doppler shift of pitch.

It became obvious in this deadly game that quick response to the information carried in the echo signals was the key to successful attack. The Commanding Officer aboard ship had to understand the operation and limitations of his sound gear if he were to counter U-boat evasion maneuvers. This need was incorporated into sound school planning.

NDRC Assistance to Sound Schools

The increase in ASW surface ship platforms required a very large increase in the number of enlisted men and later officers who had to be selected and trained to operate or understand the operation of sound gear. A group of psychologists, physicists, and communication engineers from the New London

[7]S.E. Morison, "History of United States Naval Operations in World War II, Volume I, The Battle of the Atlantic, September 1939—May 1943, pp. 220-221.
[8]NDRC, Division 6, Vol. I, Op. Cit., Chap. V.
[9]Summary Technical Report of Division 6, NDRC, Volume I, A Survey of Subsurface Warfare in World War II, 1946, Chap. 4.

Laboratory was assigned to work with the Key West Sound School, and similar assistance was furnished by the San Diego Laboratory to the San Diego Sound School. With the help of Dr. Harvey Fletcher of the Bell Telephone Laboratories, tests were devised to select trainees with aptitude to recognize and differentiate the echo, a relatively pure tone, from broad-band background noise. Trainers of various types were copied from the United Kingdom and modified to meet United States needs.

Operator/Officer "Sonar" Training[10]

An investigation disclosed that due to an oversight, a petty officer rating system had not been established for sound operators to parallel that existent for other specialities; e.g., radio electrician, signalman, etc. With no rating in their training area, the sound operators who joined their ships would "strike" for an established rating to earn more money as well as increased status in the Naval system. After this oversight was identified a petty officer rating was quickly established. The new acronym "SONAR" devised by the Harvard Underwater Laboratory for the sound equivalent of the radio frequency "RADAR" was applied to the new petty officer rating. Initially the acronym had no direct alphabetic significance; the so-called Sound Navigation and Ranging (SONAR) definition was introduced later on. In any event the establishment of the petty officer rating with the designation of "SONARMAN" stopped the attrition and improved the morale of the operators of the sound gear.

Figure 2 shows the cumulative totals of ASW ships, and personnel trained to operate or understand the operation of sonar gear. By the end of the war, more than 16,000 sonar operators were trained and special courses given to 4,000 officers, including about 2,200 prospective commanding officers. More than 2,600 sonar-equipped ASW ships were built and equipped, mostly in 1943. The sonar pool effectiveness was greatly increased after 1942 by improved training and the establishment of the above mentioned sonar rating. The magnitude of this effort and its accomplishments in so short a time were truly remarkable.

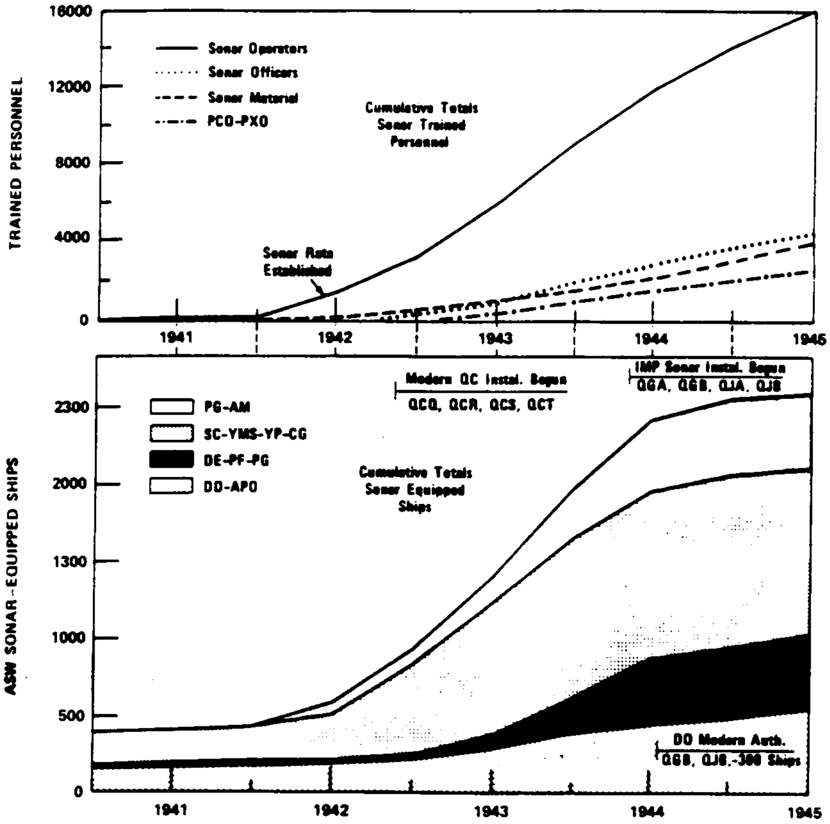
Equipment Status, 1941[11]

The existing gear, developed by NRL in the mid-1930's, could reliably detect a submerged submarine at a distance of 1 mile. The gear searched around with beams of sound about 20-deg wide, with a "ping-listen" operation on each bearing. About 4 min were required to complete a 360-deg sweep. When a return echo was received, a timing circuit determined range, and the bearing was read by comparing the direction in which the transducer was trained with the ship's heading given by a gyrocompass. As target range and bearing were furnished by the sonar operator, the course and speed of the submerged submarine were plotted, and the attack was carried on by making runs across the track of the submarine and dropping depth charges from the escort's stern at the proper moment. As the target was closed, a minimum range was reached (as shown in Fig. 3) when the limited depression angle capability of the hull-mounted gear lost contact with the target. About the last minute of the attack plot (as shown in Fig. 4) was done on dead reckoning.

ASWORG assessments and the conclusions of NDRC headquarter's investigation indicated that the gear coming off the assembly lines was too complicated for raw recruits to operate with reasonable skill after a relatively short training period. Therefore, the Harvard and New London Laboratories were instructed to concentrate on "add on" modifications to simplify operation. These came in great profusion, and only a few of the more significant developments can be cited in this article.

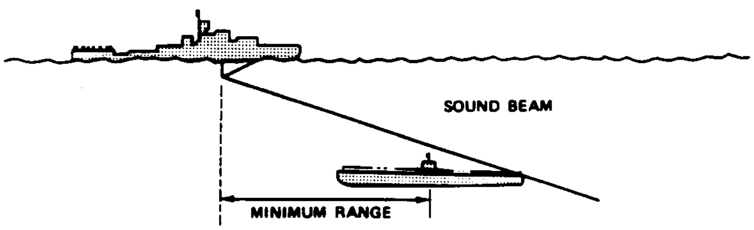
[10] "A Survey of Subsurface Warfare in World War II," Summary Technical Report of Division 6, NDRC, Vol. I (1946), pp. 231-233.

[11] C.M. Sternhell and A.M. Thorndike, "Antisubmarine Warfare in World War II," OEG Report 51 (1946), Chap. 11.



The top part of the figure shows the cumulative totals of sonar trained personnel for the time interval of 1940-1945. For the same time abscissa the bottom part of the figure shows the totals of sonar equipped ships that eventually used the 16000 trained personnel (by 1945).

Fig. 2. Cumulative Totals—ASW Ships and Personnel



(In 1942 minimum range for lost contact was about 170 yds. As the war proceeded submarines went to deeper depths when attacked. In 1945 minimum range was about 270 yds.)

Fig. 3. Minimum range of submerged submarine under attack

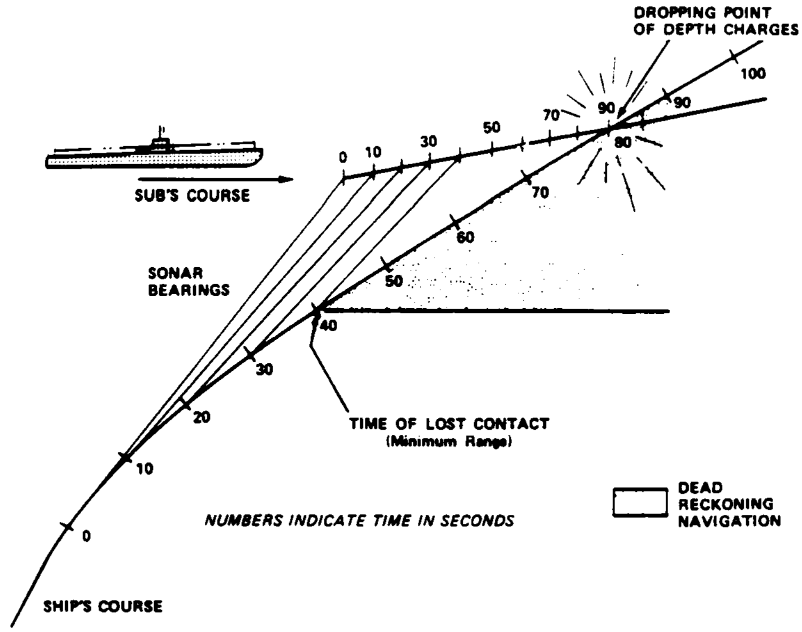


Fig. 4. Plot of typical attack

Modifications to Improve Operation[12]

Sonar Dome Improvement

The QC magnetostrictive transducer, shown in Fig. 5, and previously discussed in Ref. (1), was banjo-shaped and was mechanically trained to scan 360-deg. In order to prevent degassing and cavitation because of local flow effects, the Navy in 1942 used a spherical shaped dome as illustrated in Fig. 6. This sphere mechanically rotated with the transducer, i.e., a thin "window" section was always located in front of the transducer to transmit the sound. NDRC, utilizing the advice of the British and their own hydrodynamicists, developed an improved fixed type of dome (shown in Fig. 7), to (a) decrease the self-noise caused by the flow near and around the transducer, and to (b) house a sound baffle-sound absorber to minimize the noise from its own screws, as well as to decrease the sound reflection within the dome.

Reverberation-Controlled Gain (RCG)[13]

One of the most important modifications to the QC equipment in production and in the Fleet was the incorporation of a control to minimize the loud burst of the reverberation return after the initial ping. This loud noise reduced the operator's acuity to hear the weak echo. The Harvard Laboratory devised a circuit, called the "reverberation control of gain," (RCG) to reduce the reverberation "bang" on the operator's ears yet bring the gain up shortly so that the full-signal contrast was preserved between echo and background.

[12] Principles of Underwater Sound, Op. Cit., p. 151.
[13] NDRC, Division 6, Vol. I, Op. Cit., Chap. 11.

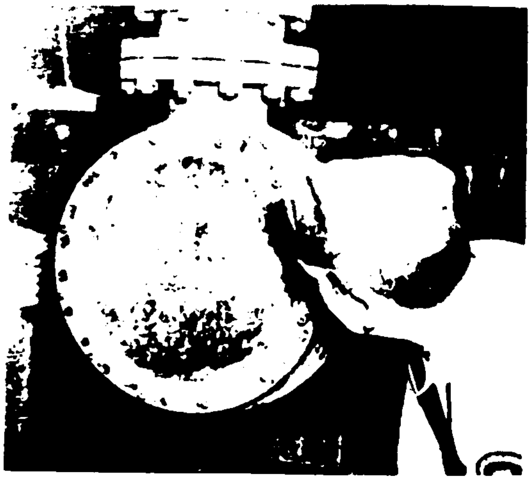


Fig. 5. QC-type transducer inspected in dry dock

Fig. 6. Spherical dome developed before war (figure reproduced from Ref. 12)

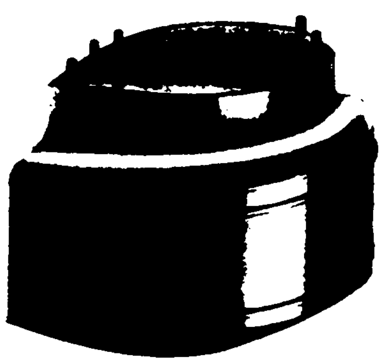
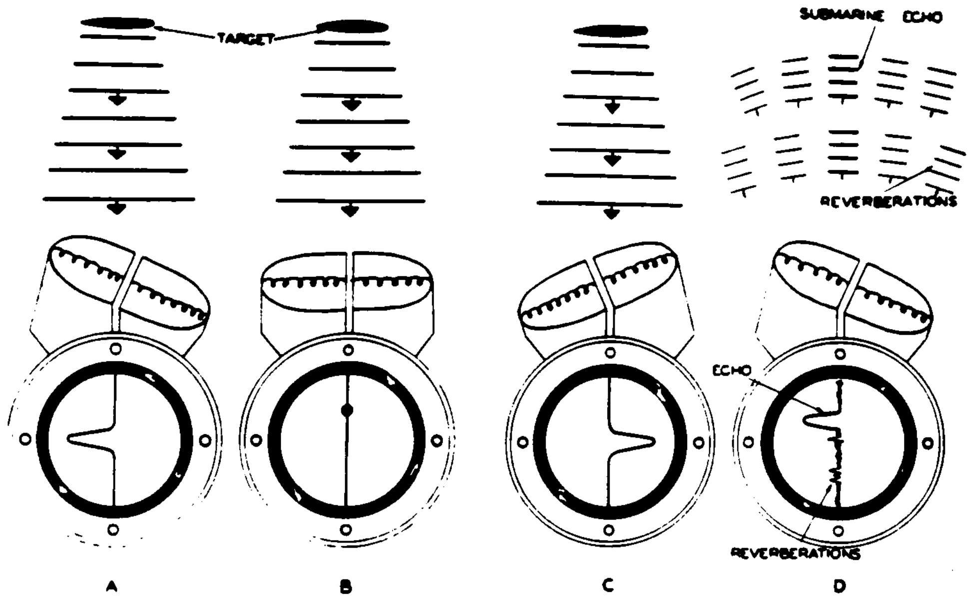


Fig. 7. Streamlined dome (with internal sound baffle) introduced in 1942



(A) Target to Port causes the deflection of oscilloscope trace to the left;

(B) Target directly in center of beam;

(C) Target to Starboard causes deflection to the right;

(D) Echoes to be distinguished from reverberation. For this purpose the visual perception is supplemented by listening to a loudspeaker.

Fig. 8. Diagrams illustrating the operation of the Bearing Deviation Indicator, BDI (figure reproduced from Ref. 13)

Bearing-Deviation Indicator, (BDI) and Maintenance of True Bearing, (MTB)

Once an echo was received, two other modifications simplified the determination of true target bearing so that the position of the target could be determined quickly and furnished to the attack team. These were two modifications devised by Harvard: the "bearing deviation indicator," (BDI) and maintenance of true bearing, (MTB). Figure 8 illustrates the operation of the BDI. The two halves of the transducer were split, and through phase-lag circuits the presentations for target to the port of the projector bearing, on bearing and to the starboard of projector bearing are shown. The BDI permitted the operator to determine with a single echo whether his projector was trained on target and eliminated the need to ping on either side and then split the difference to obtain bearing angle. The "maintenance of true bearing" (MTB) coupled the gyrocompass system to the projector motor, so that true instead of relative bearing was provided to the operator. This information was very important in case the attacking ship changed heading: it eliminated the confusion on the part of the operator as to where to train to hold the target.

Console Stack[14]

These modifications and others were incorporated into a newly introduced "console stack," which increased the ease of manipulation by the sound operator. As many functions as possible were rendered

[14]Principles and Applications of Underwater Sound, NDRC, Division 6, Vol. 7 (1946), p. 148.

nearly automatic, and ear and eye presentations were developed to give the operator a graphic picture of the situation at all times. New London pioneered in the "human engineering" effort and profited from their interrelations with the Key West Sound School training program. Figure 9 shows a photograph of the QGB equipment-console with the principal controls identified.

ASW From Aircraft[15]

Columbia University, through its various laboratories, was tasked with different projects to improve aircraft capability to locate submarines on the surface and then, if attack at this point did not succeed, to continue to follow the submarine's course (magnetically or acoustically) so that either further attacks could be managed, or surface ships could be vectored in to take over the search.

Magnetic Airborne Detection, (MAD)

The first magnetic airborne detector (MAD) used to locate submarines was a modification of the Vacquier magnetometer produced by the Gulf Research and Development Company in peace time to explore areas for oil deposits. Subsequent improvements were made to compensate for the magnetic fields of the aircraft, as well as for noise caused by rapid plane maneuvers. Between July 1941 and 1944, about 400 installations on ASW aircraft were made and proven useful when a submarine was located by radar and then submerged before the aircraft could reach it. MAD was also used for blockade patrols over small strategic areas (e.g., Gibralter). However, despite continued efforts to improve the technique, typical ranges of about 600 ft represented the wartime capability of this gear to locate submarines. J.S. Coleman, the NDRC authority on antisubmarine detection equipment development indicated that during the last part of World War II MAD was supplanted by the expendable radio sonobuoy.[16]

Expendable Radio-Sonobuoy

The expendable radio sonobuoy was developed at the New London Laboratory to allow a ship, airplane or blimp to deploy a buoy and then receive the sounds detected by the buoy hydrophone by means of broadcast radio signals. The initial idea of the development was that a surface ship could drop this device astern and detect signals of a pursuing submarine. Its main use, however, was to be from aircraft and blimps. The buoy was dropped from the air by means of a self-contained parachute. Upon striking the water, an impact catch released a hydrophone which sank to a water depth of 20 ft. The buoy then broadcasted high-frequency-radio signals to a range of about 35 miles while the listening aircraft was at an altitude of 5,000 ft. The life was about 3 hours, after which a plug was dissolved and the device sank. Six frequency channels in the plane's receiver allowed the simultaneous use of a like number of buoys. The buoys were deployed in patterns so that the simultaneous use of multiple buoys could locate the submarine target. Generally, fixes were not good enough for the plane itself to attack the submerged target, but very useful for the plane to vector a surface ship using hull-mounted sonar for final attack. More than 160,000 units were ordered during the war.

Team ASW—Surface Ships and Aircraft[17]

In an early study, ASWORG analyzed the capabilities of the Type VII and Type IX U-boats that were the backbone of the German submarine force for most of the war. These crafts were like most of the submarines of this era, submersible surface craft. To operate they had to proceed on the surface most of the time, and only submerged either in the final stages of attack or during escape maneuvers.

[15] NDRC, Division 6, Vol. I, Op. Cit., pp. 190–195.
[16] NDRC, Division 6, Vol. I, Op. Cit., p. 177.
[17] NDRC, Division 6, Vol. I, Op. Cit., Chap. VII.

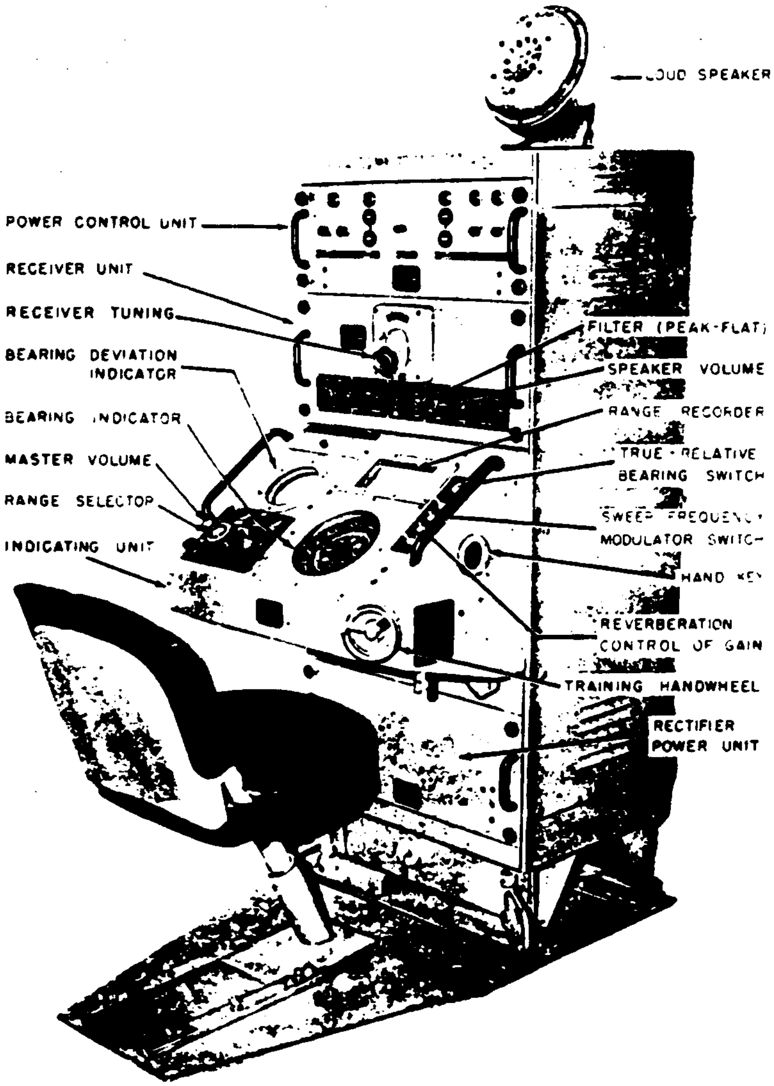


Fig. 9. Model QGB sonar console stack; the principal units are identified in the preceding paragraph (figure reproduced from Ref. 14)

TABLE II
Sweep Rates Under Various Conditions (In Sq Mil/Hr

Aircraft			Surface Ships		
	Surfaced Sub[b]	Submerged Sub[c]		Surfaced Sub[a]	Submerged Sub[b]
Visual (good visibility)	1,250	Approx 0	Visual	Approx 0	Approx 0
Radar-ASG	2,500	Approx 0	Radar (10 cm)	100	Approx 0
MAD[a]	25	15-20	Sonar	15	15
Sonobuoys[a]	200	15			

[a]Operational experience showed that classification of MAD and Sonobuoy contacts as well as accurate location for effective attack was also difficult.
[b]During the last half of the war most of the kills of surfaced submarines were by aircraft.
[c]During the entire war most of the kills of submerged submarines were by surface ships.

With their limited endurance when submerged, to conserve battery, *they had to travel at low speeds (approximately 3 knots)*, and when sound conditions were good, they were fair game for sonar equipped surface ships.

A typical situation was one in which one or more destroyers were called to the scene of action by an aircraft which had made an initial sighting and forced the submarine to dive. The destroyers arrived a certain time late after the sighting, and ASWORG, knowing the underwater speed and endurance of U-boats as well as the capabilities and limitations of hull-mounted sonar, had to devise a search plan for the destroyers to relocate the submarine as soon as possible. The rate of search and the "swept area" vitally depended on optimum use of the equipment and the sound propagation conditions. Team activity of multi-ship sweep—three destroyers hunting in a line abreast, for example—were more than three times as effective as one destroyer hunting alone. In addition, it also turned out that aircraft patrolling around the search area were invaluable for relocating a submarine that had surfaced and tried to escape at high speed.

The sweep rates of aircraft and surface ships against surfaced and submerged submarines are shown in Table II. From this table it is evident that aircraft available for search were superior platforms for locating submarines on the surface; however, once the submarine submerged the surface ship had the edge to drive home an attack, despite the relatively high numbers shown for MAD and expendable sonobuoys. Operational experience showed that classification was difficult with MAD and that the localization of target for accurate attack was difficult with the deployed sonobuoys.

By 1943 Allied aircraft flying off escort carriers had the weapons and technology to locate and destroy surfaced U-boats. Radar and Loran enabled the detection and pinpoint location of targets. Rockets and airborne depth charges could destroy U-boats on the surface or caught just diving. If the target was driven below and attempted to escape, surface ship forces by this time had improved their kill efficiency from less than 5 to about 20 percent. At this time, one surface ship attack out of five succeeded in killing the submarine.

It was because of the success of these air-sea coordinated attacks that the Germans started the construction of a submarine difficult to detect from the air and destroy from the surface. This was the Type XXI, with both snorkel capability to evade the aircraft search radar *and high-submerged-speed capability (because of special batteries and ship streamlining) to evade the surface ship sonar attack.* Fortunately, for the Allies, production problems delayed the introduction of sizable numbers of these advanced crafts until the war was over.

Surface Ship ASW Weaponry Improvements[18]

Hedgehog and Mousetrap

When Division 6 surveyed the state-of-the-art in surface ship antisubmarine weapons in 1942, if found that the only new development since the depth charge of World War I was the British "Hedgehog" system (shown in Fig. 10). Each of the projectiles contained 30 lb of torpex explosive, which, when striking, could penetrate the submarine's pressure hull. Explosion occurred only on contact. Each salvo covered an area of about 110 by 120 ft. As the British indicated, "The advantage of the shotgun over the rifle in the probability of making hits was obtained." However, the barrel of the "shotgun" was affected seriously by the rise and fall of the deck. In addition, the charges thrown forward by only 200 yd required prompt change of course by the attacking vessel to avoid finding itself on top of an explosion in case a hit was made; a hit by any one of the charges usually detonated the rest. A tremendous advantage, however, was that if the salvo missed, no Asdic interference resulted, as it did with conventional depth charge attack.

The United States duplicated the British installation on many of the newly constructed ASW vessels, but analysis showed that the recoil of the installation was too severe to use on vessels smaller than destroyer escorts. The development of a smaller rocket weapon for this purpose was pushed with great vigor by the California Institute of Technology, and within 6 months of initial design, the "Mousetrap" rocket, together with a simple launcher and a new fuse, was developed, demonstrated, and accepted for installation on patrol craft. The urgency of the need led the Bureau of Ordinance to request NDRC to undertake the immediate manufacture of ammunition, launches, and fuses. To keep the recoil down, the Mousetrap rockets were half-size duplicates of the Hedgehog and only six were launched at a time. These were launched 220 yd ahead of the ship, but at right angles to its course so as to minimize the maneuvers necessary for the PC to avoid detonation damage.

Squid

The "minimum range" problem for surface ship sonar, as previously described in Figs. 3 and 4, received considerable attention in the United States and United Kingdom in early 1943. In the United States, New London developed a mechanical tilt transducer to use for the last stages of localization. Obtaining a tilt angle on the target (as shown in Fig. 11), furnished the information from which the depth of the target could be calculated. In addition, by tilting the beam, the signal to reverberation ratios improved. A parallel endeavor also took place in Britain at this time, with the major difference that instead of mechanically tilting the transducer, a second transducer electrically steered at a higher frequency (50,000 cycles per second) was mounted above the first.

However, by the time both equipments were being tested, in late 1943, events started to show that the tide had turned to favor the Allies in the Battle of the Atlantic. New London's effort was then redirected to improve the prosubmarine capability in the Pacific. The British continued their development, and by 1944 they had produced a remarkable apparatus called the "Squid." This was an attack system that consisted of three ahead-thrown depth charges with the target's actual depth (as determined by the tilt-beam sound gear) set automatically into the depth charge fuse just prior to launch. (It should be noted that by 1943 the Type VIIC U-boat could dive to 900 ft without harm. Diving deep was a standard maneuver when under attack.)

Acoustic Torpedoes[19]

German "Destroyer Killer"

By 1943 Allied surface ship sonar had improved its kill-per-attack capability from 5 to about 20 percent. Therefore, to allow offensive as well as defensive action against surface ASW forces, the Germans

[18]Sternhell and Thorndike, Op. Cit., pp. 115-125.
[19]Sternhell and Thorndike, "Antisubmarine Warfare in World War II," OEG Report Number 51 (1946), Chap. 15.

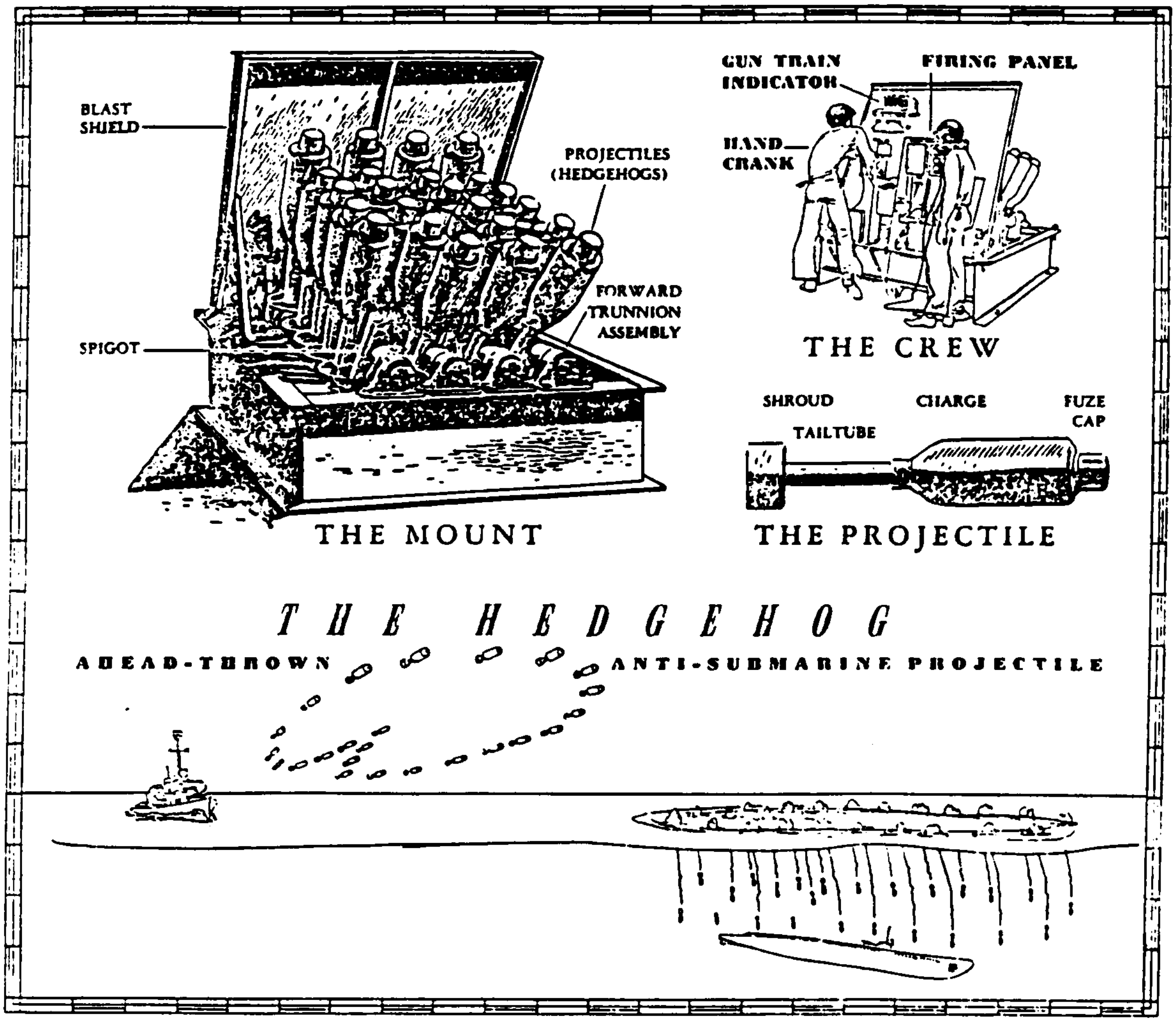


Fig. 10. Representation of HEDGEHOG (figure reproduced from T. Roscoe's U.S. Destroyer Operations in World War II, US Naval Institute, 1953, p. 60)

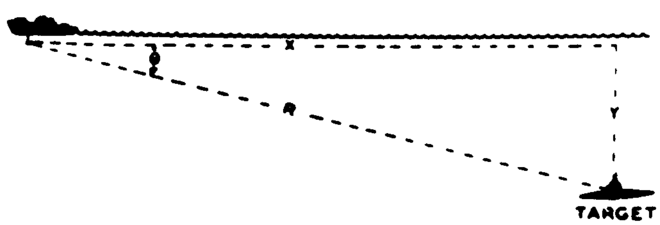


Fig. 11. The geometry of depth determination

developed the T4 acoustic homing torpedo, described by the Goebbels propaganda machine as the "Destroyer Killer." Introduced in September 1943, this weapon sank about 25 escorts and 20 merchantmen durng the war.

Its operation was as follows: the propulsion drive was a conventional German electric torpedo slowed to 20 knots to minimize self-noise from the acoustic sensors at the nose. When the Torpedo was fired on an approximate collision course, gyro control persisted until the cavitation noise of the target's propellers was heard by the torpedo's hydrophones. Then relayes allowed acoustic-homing steering to take over. Then, the torpedo closed until the pistol detonator triggered the warhead. The noisier the ship, the greater was the homing range.

"Foxer" Countermeasure

Because the United Kingdom and the United States were both in the process of producing their own version of a passive homing torpedo, ASWORG and its British opposite quickly devised countermeasures. The most successful was a towed noisemaker system utilizing the high-level acoustic output produced by banging together a set of parallel pipes, or parallel bars. The pipes or bars were in a frame which when towed through the sea were hydrodynamically forced to strike together repeatedly. The high-level output had been previously used to sweep acoustic mines when the device was towed by a minesweeper. After careful analysis the United Kingdom concluded that *two* such noisemakers should be towed 200 yd astern in tandem, but separated by 100 yd. The analysis showed that the position had to be out of the ship's bubble wake to assure that own ship would be free of homing attack. The pair of parallel pipes plus their depressor-diverter systems was called "Foxer" by the United Kingdom and FXR by the United States. By January 1944 FXR Mk2 (suitable for tow speeds from 12 to 19 knots) was getting general use by large escort vessels. Other versions were developed for smaller ASW vessels.

American Acoustic Torpedo Development[20]

The idea of making a torpedo with acoustical steering dated back to World War I. Repeated attempts to do so between the wars were defeated by the high-level self-noise that prevented hydrophones at the torpedo nose-section from hearing targets. Therefore, in 1941 there was much skepticism in many sections of the Bureau of Ordinance when NDRC started the research and development for an air-dropped (!) acoustic homing torpedo. The current view was that making a submarine or surface ship launched weapon was difficult enough; having it dropped from an aircraft and withstand the shock of entry acerbated the difficulty. The following specifications were submitted to NDRC:

Propulsion: electric, single-rotating motor
Power Source: lead storage battery
Speed: 12 knots
Range: 200 to 2,000 yd
Explosive Charge: 100 lb
Dimensions: 84 in. long, 21 in. in diam.
Homing: acoustical
Launching Method: from aircraft making 125 knots at 250 ft altitude
Depth Capability: 600 ft.

NOTE: 12 knots was considered adequate to overtake and attack the slow submerged speed MK VII and XIX U-boats.

For security reasons the device was called a mine rather than a torpedo. NDRC organized parallel developments convemed with:

[20] "Acoustic Torpedoes," Technical Report, Division 6, NDRC, Vol. 22 (1946), Chap. 5, 6, and 7.

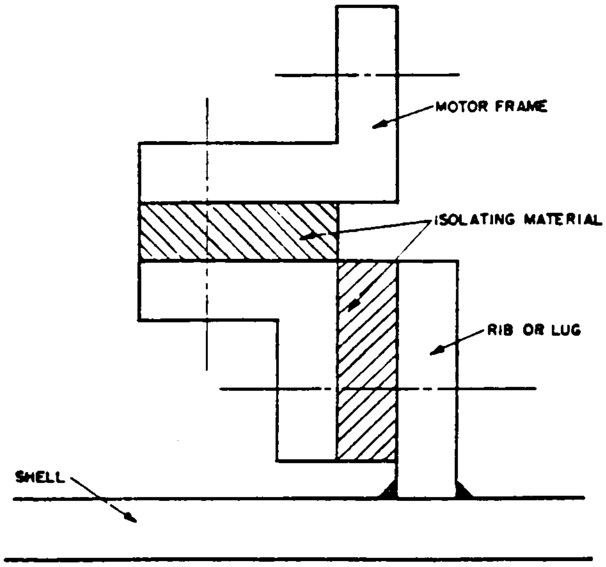


Fig. 12. A schematic illustration of a method that isolates against shear vibrations only

external and internal structure design to meet problems of shock, vibration, and acoustical considerations;
power, propulsion, and steering;
stability and control;
propulsion and auxiliary machinery silencing; and
development of hydrophones and electronic mechanisms for steering in azimuth and elevation.

The Harvard Underwater Sound Laboratory, and the Bell Telephone Laboratories did outstanding research and development on the acoustic problems of the Mk 24 torpedo. Harvard studied the noise caused by flow effects at the propellers and tail-cone assembly; Bell systematically investigated techniques to minimize the coupling of machinery vibration to the outer skin. Bell also devised simple mounts that minimized the transmission of sheer vibrations, as shown in Fig. 12. These mounts worked well both in air and in water. (It should be noted that shear mounts work well in water while compression mounts generally do not isolate from vibration.) Typical mechanisms of self-noise as described in 1943-and many times since rediscovered are shown in Fig. 13.[21,22] The torpedo was quieted by minimizing, mechanical vibration as well as by carefully controlling the onset of propeller cavitation. In the process of analyzing noise, Bell introduced the use of the Spectrum Analyzer to provide amplitude and frequency measurements as a function of time. (An additional discussion of the Spectrum Analyzer will be presented later in this report.)

By 1944, the air-launched antisubmarine "mine" had successfully passed fullscale trials; however, from available data it does not appear that it was deployed in large numbers. One can only speculate that since the Atlantic war was going well, the weapon was held back lest the Germans capture a unit and furnish its details to the Japanese. The protection of our Pacific prosubmarine effort was a major worry of the Navy at this time.

In 1943, the demonstration that acoustic torpedoes were feasible coupled with the appearance of the German T-4 resulted in a change of torpedo program emphasis. The NDRC now was instructed to develop an *antishipping* acoustic torpedo. Table III lists some of the operational units developed.

[21] K.C. Morrical, R.S. Alford, and others, "Self-Produced Noise From a Mark 24 Mine," Husland BTL (Jan. 9, 1943).
[22] Final Report, Mark 28 Torpedo, History, Principles of Operation, Field BTL, (Aug. 20, 1945).

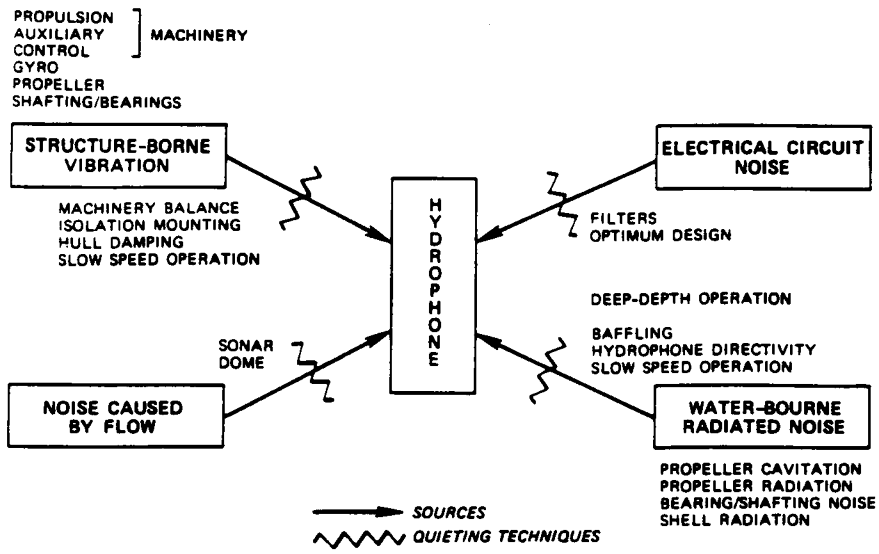


Fig. 13. Summary torpedo hydrophone self-noise sources and quieting techniques (Circa 1943)

TABLE III
NDRC Torpedo Development Program (Acoustically Controlled Torpedoes)

Original Model Designation	Description	Project Number	Acoustic Control Specifications	Final Acoustic Model Designation (Mk)
Antisubmarine Mine	Small-sized, stubby, electrically powered; 12 knots	(NO-94) (Fido) project 61	Air-launched, antisubmarine; acoustic homing control	24* 27* (revamped 24)
Mk 18	Antisurface ship, electrically powered; 20 knots	NO-157	Submarine-launched, antisurface ship; acoustic homing control	28 (20 knots)* 29 (25 knots) 31 (28 knots)
Mk 20	Antisurface ship, electrically powered; 39 knots	NO-157	Submarine-launched, antisurface ship; acoustic homing control	20 (37 knots)
Mk 13	Antisurface ship, steam driven; 33 knots	NO-149	Air-launched, antisurface ship; acoustic homing control	21 (33 knots)
Antisubmarine Mine	Small-sized, stubby, electrically powered; 12 knots	NO-181	Ship-launched, antisubmarine; echo-ranging homing control	32 (12 knots) (also air-launched)
Mk 18	Antisurface ship, electrically powered; 29 knots	NO-181	Submarine-launched, antisurface ship; echo-ranging homing control	18, echo-ranging model, (Untested)

*Used successfully in World War II combat.

Fig. 14. Exploded vibrational isolation for self-noise control showing the vibrational isolation of the high-speed steam turbine, the vibration-isolating forward joint ring with a bayonet lock joint for easy access to the control equipment in the nose, and the vibration-isolated hydrophone mounting (figure reproduced from Ref. 17)

Quieting techniques allowed the use of a modified *steam* driven torpedo, a feat heretofore considered impossible. The Mk 21 steam turbine, as illustrated in Fig. 14, was effectively isolated from the shell. The type of electronics in use at this time is shown in Fig. 15. All vacuum tubes had to be vibration isolated from the chassis, and care had to be used to mount the bulky condensers, relays, and coils.

Blimp-Towed Hydrophone[23]

In 1942, to assist the protection of coastal shipping, various acoustic sensors were towed from blimps. Figure 16 shows a blimp-towed hydrophone that consisted of a hydrophone, cable, and diving tractor. The streamlined hydrophone consisted of a 2-in.-diam-body, 4-ft long with a tapered weighted nose and stabilizing tail. The tractor served to separate the hydrophone from the water-entry noise of the cable-towing arm arrangement. The lightweight cable reel used to raise and lower the hydrophone gear is shown in Fig. 17. The slip of the reel was adjustable to relieve the cable from transient loads and was operated by an electric motor or by hand. The cable had to be shielded to minimize the pickup of radio frequency signals, especially r.f. "Fox" transmission below 20,000 cycles per second.

The system towed to 25 knots with a minimum of water noise. With good sound transmission conditions, freighters could be heard to ranges up to 15 miles while towing at speeds to 25 knots. Because of problems of r.f. and electrical noise as well as towing fatigue failure of the strength members of the cable, the towed system was abandoned in favor of sonobuoys.

[23]NDRC, Division 6, "Listening Systems," Vol. 14 (1946), pp. 68, 69.

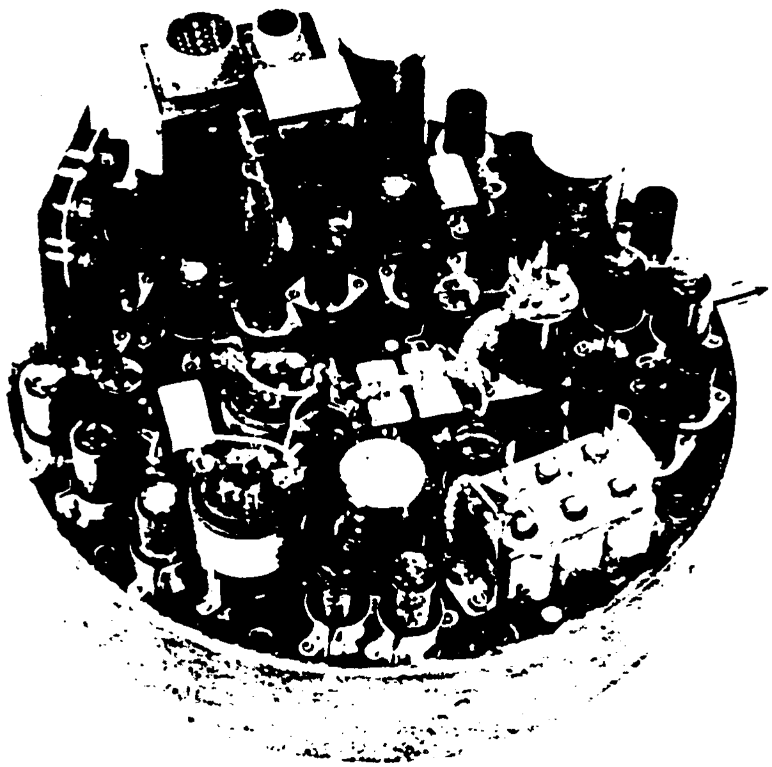


Fig. 15. Control chassis for the echo-ranging mine; it contained a complete echo-ranging transmitter and receiver (figure reproduced from Ref. 17)

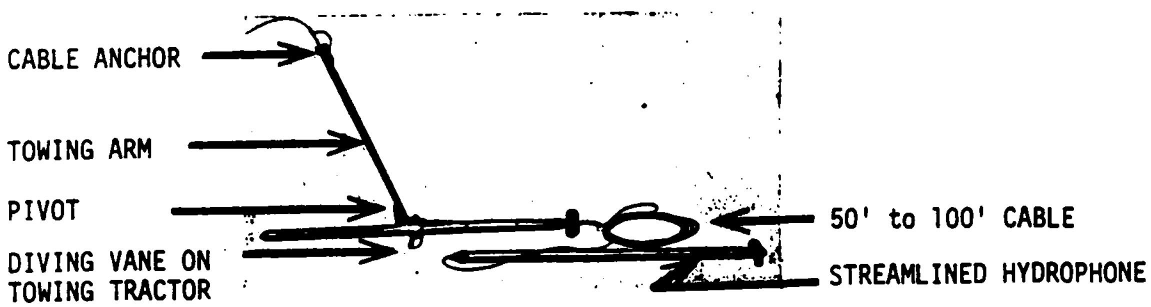


Fig. 16. Blimp-towed hydrophone (figure reproduced from Ref. 23)

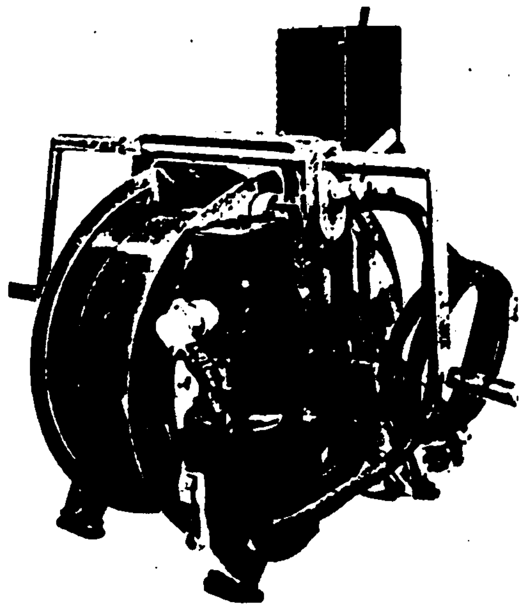


Fig. 17. Light weight cable reel (figure reproduced from Ref. 23)

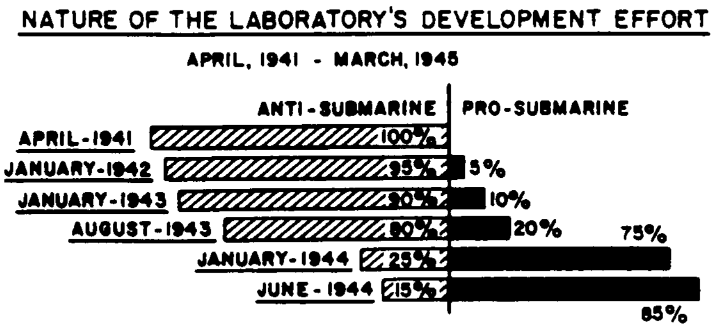


Fig. 18. Relative anti- and pro-submarine effort at the New London Laboratory from April 1941 to March 1945

PRO-SUBMARINE RESEARCH AND DEVELOPMENT[24,25]

At the beginning of World War II, the Navy had emphasized antisubmarine warfare in the Atlantic over the prosubmarine needs of its submarine force in the Pacific. However, in mid-1943 successes against U-boats and the comparative absence of Japanese submarine activity allowed a change in priorities. NDRC was requested to decrease antisubmarine in favor of prosubmarine effort. Figure 18 shows the shift in emphasis that took place at the New London Laboratory, a shift that was representative of the trend of Division 6 as a whole.

The New London Laboratory was in the forefront of prosubmarine activity. The Laboratory had been assigned the problem of improving listening on submarines in 1942 as a result of a recommendation of the previously mentioned Colpitts' Report. In the process of working on this problem, teams had visited submarine bases at New London and Pearl Harbor and become thoroughly acquainted with submarine operation and tactics. By the end of 1942, an experimental JP sonic listening system was installed on a submarine. The new gear improved the ability of the sound operator to detect and identify targets, but disclosed deficiencies on our own submarines. Sonic listening disclosed that our own ships when operating submerged (in the absence of propeller cavitation) had many noisy machines. Especially prominent were the tonal "whine" sounds from auxiliary machinery when the boat operated at low speed. As a result, the Bureau of Ships increased emphasis to quiet our submarines and promoted the interaction of the sonar activity with submarine machinery designers to minimize interference with own sonar as well as to decrease the possibility of detection by passive enemy listening gear.

24 J.P. Baxter, Op. Cit., pp. 184-185.

25 T.E. Shea and T.K. Glennan, "A Summary of the Work of the New London Laboratory on Equipment and Methods for Submarine and Subsurface Warfare, 1941-1945," NDRC No. 2337 (1945).

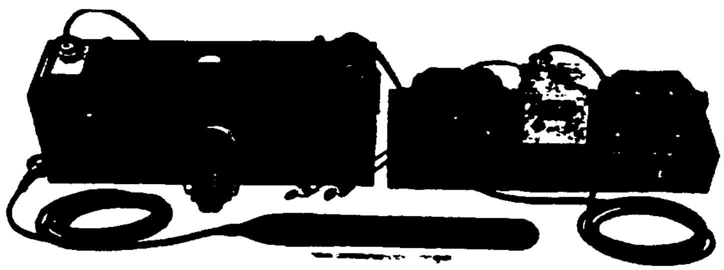


Fig. 19. Model OAY sound measuring equipment (figure reproduced from Ref. 26)

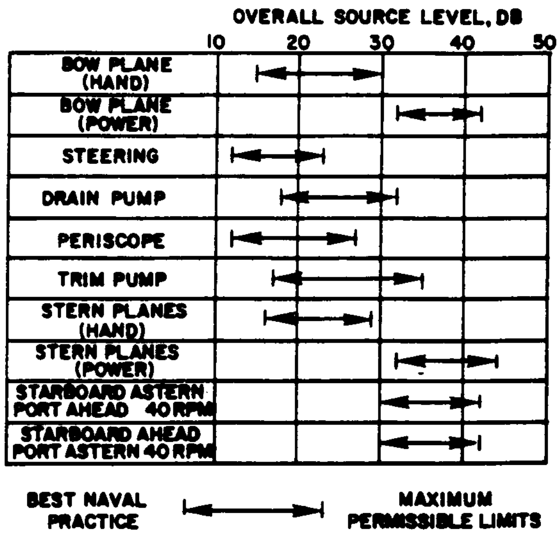


Fig. 20. Suggested limits of overall sound level of several auxiliaries on submarines, and the levels representing best naval practice

OAY Sound-Measuring Equipment[26]

The New London Laboratory initiated a program designed to study methods of reducing submarine noise and to develop methods to measure the noise quantitatively. The first step was to develop a standardized noise-measuring apparatus that could be used wherever submarines were being built, overhauled or operated at sea. The OAY sound measuring equipment (shown in Fig. 19), was developed in 1943 and adopted by the Bureau of Ships. This apparatus served as the standard measuring device (other than on sound ranges) for the radiated noise from submarines. Special emphasis was given to the quieting of the sounds of machinery used when the submarine operated submerged on battery. With the submarine surfaced and tied to a pier or buoy, individual auxiliary machinery was measured and techniques worked out to establish standards for machinery acceptance either in new construction or subsequent overall. Figure 20 shows a listing of several auxiliaries and the sound limits for the best naval practice and maximum permissible limits. Note that permissible overall sound levels for a given machine could vary as much as 15 dB.

[26]Subsurface Warfare, Op. Cit., NDRC Division 6, Vol. I, p. 204.

At this time the Bureau of Ships laboratories were working on problems of shock isolating machinery from the hull. Harvard and New London provided assistance to determine whether sound isolation could also be incorporated into these mounts. In addition, the research laboratories of General Electric and Westinghouse especially contributed expert assistance in minimizing bearing noise and vibration caused by machinery unbalance. With many submarines coming off the assembly lines, a feverish effort ensured that the new boats were equipped with the best quieting techniques that the state-of-the-art allowed.

Environmental Noise Baffling by Air-Bubble Screen[27]

Any history of the dockside measurement program would not be complete without mention of the Pearl Harbor ARD conversion. When New London personnel arrived at the Submarine Base at Pearl Harbor to initiate an overside measurement program for subs in overhaul, they were faced with an extremely difficult task. Many hundreds of ships were in the harbor and were being worked on "around the clock." The background noise was of such a high level that no quiet pier location could be found to do the routine tests. Indicative of the times was the way this problem was solved: the submarine was floated in a double-hulled auxiliary repair dock (ARD), and the opening of the dock was isolated from the environmental noise by means of a special air-bubble screen. When the bubble screen was turned on after the submarine had entered the dock, the noise level decreased 21 dB, sufficient to allow the standard measurements to be obtained.

Sound Range Measurements[28-30]

After each of the many auxiliary machinery items aboard a submarine was measured dockside, underway measurements were then obtained to determine the total sound field radiated from the concert of inboard and outboard sources. Two types of radiated noise measurements were obtained: measurement from a mobile platform (usually a drifting listening ship with an overside hydrophone) and measurement on a fixed sound range. The mobile measurements were usually preliminary to the fixed range testing and were accomplished near a shipyard so that obvious noise could be minimized. The fixed ranges were located off New London, Norfolk, San Francisco, Seattle, and Honolulu. The range at Norfolk was especially well equipped to measure acoustic as well as magnetic signatures of ships and submarines. In addition, at Norfolk the Naval Ordnance Laboratory (NOL) had developed a system to measure the close-in sound field of ships and submarines for the development of acoustic triggers for mines. The fixed ranges had various hydrophones located on tripod mounts off the sea bottom that were cable connected to a measurement and analyzing facility. At the terminal building, acoustic equipment was available to analyze signals generally from 100 to 25,000 cycles per second. (NOL's processors could handle signals in the subsonic range.) Analysis was made directly as well as from post-test analysis of recordings—e.g., sound on film, phono-disc, and wire recorder.

On the sound range the submarine was operated at periscope depth and on the surface. Visual sighting of the periscope was required to track the submarine and to determine its range to the hydrophones. During one of the most important runs, the submarine was maneuvered directly over the hydrophone so that principal sources could be identified and analyzed. Figure 21 shows the block diagram of the port and starboard machinery line ups of a typical fleet boat of this period, as well as the type of noise analyzed from each component.

Because of the need to have the sound ranges convenient to submarine bases and shipping traffic, coastal water locations were chosen with depths usually 200 feet or less. As a result, fluctuation caused by multipath and near-field problems made the derivation of absolute levels difficult. For engineering

[27] D.P. Loye and W.F. Arndt, "A Sheet of Air Bubbles as an Acoustic Screen for Underwater Noise," *JASA* 20, 143-145 (Mar. 1948).
[28] Ship Acoustical Surveys, U.S. Navy Bureau of Ships, NAVSHIP 250-371 (1945).
[29] V.O. Knudsen, et al., "Sounds from Submarines," NDRC Report 1306 (1943).
[30] V.O. Knudsen, et al., "Sounds from Surface Ships," NDRC Report 2124 (1945).

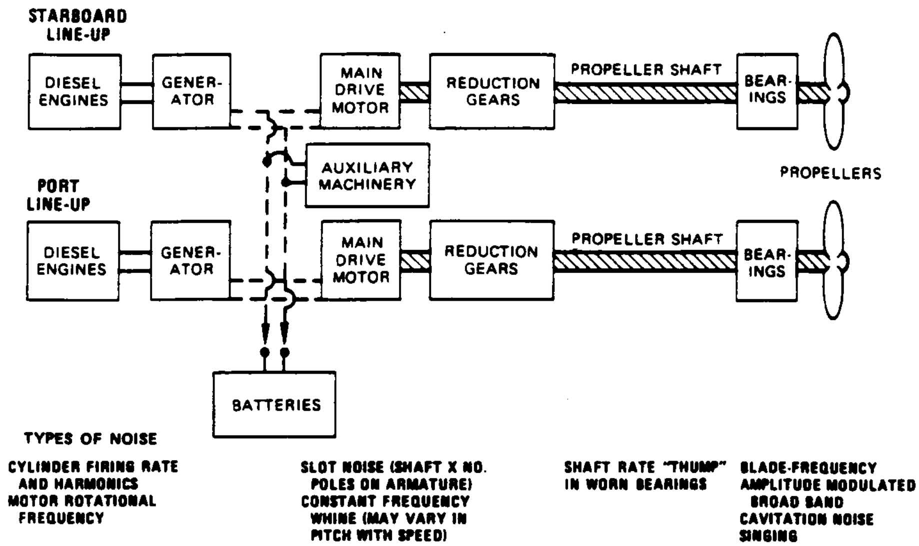


Fig. 21. Block diagram of machinery line-up, and types of noise on diesel-electric submarine of World War II

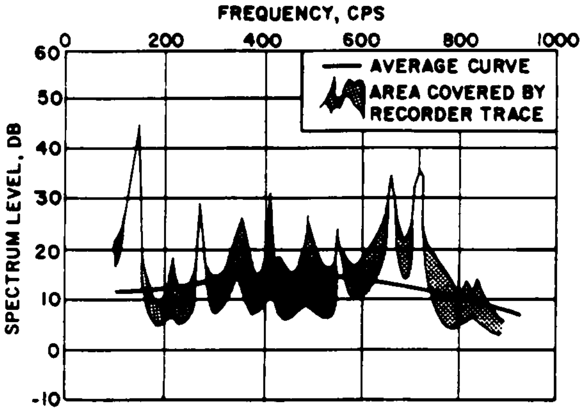
and "ballpark" design purposes "average" numbers were published despite fluctuations as those shown in Fig. 22. Measurements of average levels were compiled not only for submarines, but for hundreds of surface ships as well. Table IV presents representative levels as compiled by Dr. V. O. Knudsen and his associates from range data.

Sound-Spectrograph: Application to Noise Analysis[31,32]

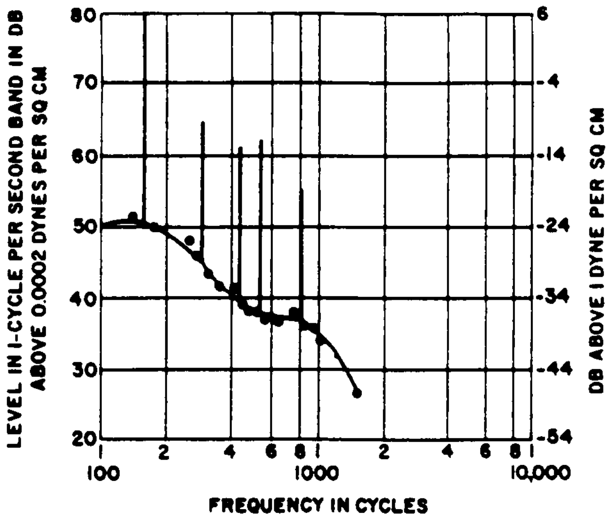
The Sound Spectrograph, which produced the sound spectrogram shown in Fig. 22(d), proved to be extremely useful in developing understanding of the nature of ship and submarine "sound signatures." This device, developed about 1939, was used by the Bell Telephone Laboratories throughout the war to crack enemy radio-telephone "scrambled" transmissions. By 1940, under NDRC contract, Bell showed that the most complicated German coding of voice transmissions could be solved. (As a result, NDRC recommended that Roosevelt and Churchill stop using the radio-telephone and communicate with enciphered teletype.) To take care of military needs in the field, a production line of units was set up with appropriate allocation of spare equipments. When Section 6 asked Bell to assist in the measurement and analysis of torpedo and ship noise, Bell adapted some of the spare units for these applications. After initial demonstration New London, Harvard and San Diego Laboratories enthusiastically put the instrument to use. By 1943, sophisticated analyses were being performed on ship and submarine sound outputs.

As an example, Fig. 23 shows a two-part record of a cargo vessel moving at 5 and then 10 knots. The upper part of the figure represents the spectrogram of the 5-knot run; the lower part, the 10-knot run. The interpretation of the record is as follows: the scale of the vertical axis represents the mid-frequency of the scanning filter (45 cps wide); the horizontal axis represents the passage of time; and the darkness of trace, relative intensity. To take care of the limitations of dynamic range, and with the prior knowledge of the nature of the cavitation noise of the target, the relative darkness was adjusted to compensate for an intensity loss of 6 dB per octave. In the top part of the figure, the 5-knot run, the successive vertical bands are propeller modulations occurring at a rate of about three per second; the nearly continuous horizontal striations represent tonal components near 1,300, 1,500, 1,700, and 1,850

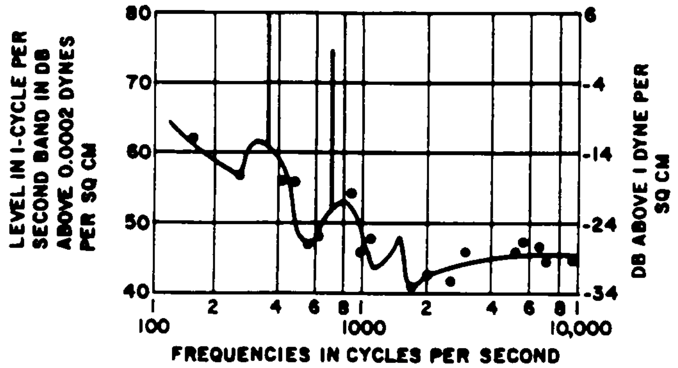
[31] D. Kahn, *The Code Breakers* (Macmillan, N.Y., 1967), pp. 558, 559.
[32] "Recognition of Underwater Sound," NDRC Division 6, Vol. 9, pp. 45-48.



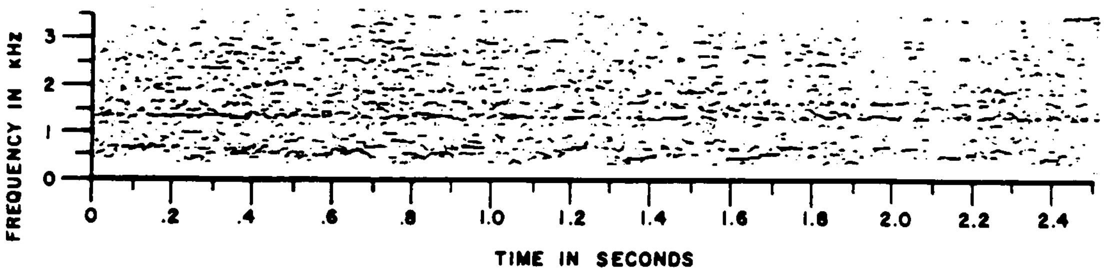
(a) Spectrum of a submarine



(b) Spectrum of a fleet-type submarine at 50 rpm (2.5 knots) and periscope depth, measured 150 yards from the screws



(c) Spectrum of a fleet-type submarine at 120 rpm (6 knots), and periscope depth, measured 170 yards from the screws

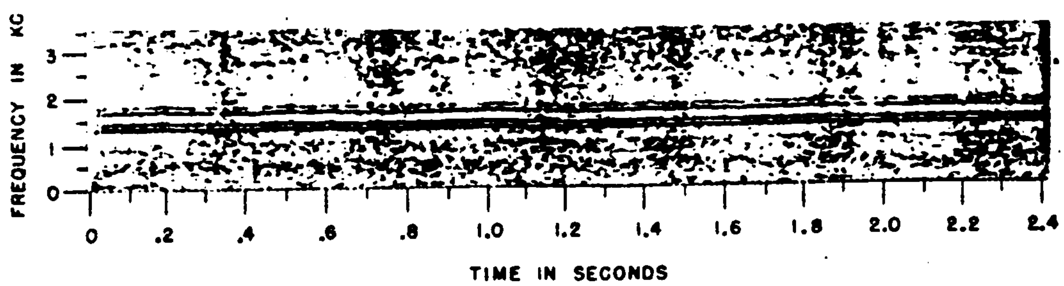


(d) Time-frequency-intensity analysis showing frequency modulation of the propeller sounds from a submerged submarine

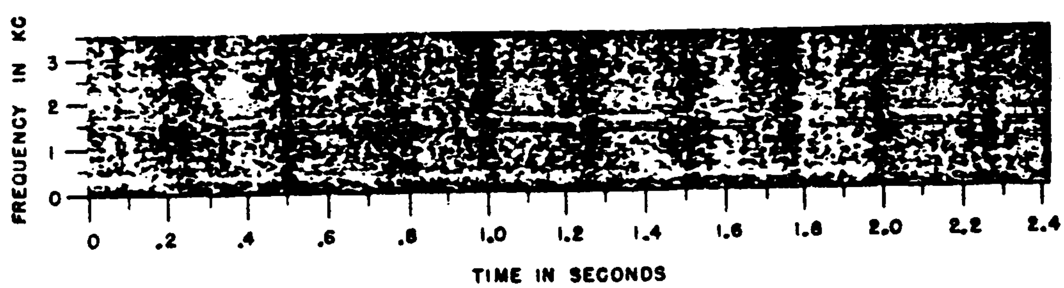
Fig. 22

TABLE IV
Typical Average Source Levels for Several Classes of Ships in dB rel to 1 dyne/cm^2 in a 1-cps Band at 1 yd (Data from NDRC Reports 1306 (1943) and 2124 (1945). Original measurements were at 20-yd range.)

Frequency (cps)	Sub at 6 knots at Periscope Depth or 12 knots on Surface	Freighter 10 knots	Corvette 15 knots	Destroyer 20 knots	Cruiser 20 knots	Battleship 20 knots
100	49	52	57	63	69	76
300	42	42	47	53	59	66
1000	32	31	36	42	48	55
3000	22	21	26	32	38	45
5000	18	17	22	28	34	41
10000	12	11	16	22	28	35
25000	5	3	8	14	20	27



(a) proceeding at 5 knots



(b) proceeding at 10 knots

Fig. 23. Comparison of sound spectrograms of cargo vessel

cycles per second. The absence of propeller modulation from these tones indicated that they were not produced by the propulsion machinery. In the lower part of the figure, the 10-knot run shows the machinery tones more nearly masked by the increased cavitation noise. Comparison of the two sets of traces shows that the modulation rate increased with speed.

In addition to providing an understanding of the nature of the noise, these records provided guidance as to the most efficient way to obtain a quantitative analysis. Rather than sweep through the entire record with narrow-band heterdyne analyzers (typical of the state of technology at the time for air-acoustic signals), narrow band analysis would be used only for the tonal components and appropriate broader band filters used elsewhere. Much time was saved in the processing of complex signals by the use of this machine.

Bureau of Ships Sound-Silencing Program[33,34]

Starting in 1942, the Bureau of Ships coordinated the activity within shipbuilding, machinery manufacturing, and research in order to achieve an average decrease of 20 dB in the radiated noise levels of 1944 submarines as compared with equivalent measurements of 1942 boats. The decrease was achieved by (a) the installation of low-frequency shock-and-vibration mountings between the machine and its foundations, and (b) the development of improved procedures for balancing rotating elements so that a minimum of vibration was generated. In addition, planning was accomplished to allow the ship "*in situ*" selection of quieter elements in machinery line up so that optimum machinery bills could be selected by the ship during various types of tactical situation; e.g., patrol, attack, and escape. The "*in-situ*" selection was accomplished by the "noise-level monitor," the NLM, described below.

Noise-Level Monitoring (NLM) System

In order to monitor ownship noise, four special magnetostriction hydrophones were installed along the hull near locations known to radiate high level noise. The cables from these units were brought to a special amplifier and meter that allowed the noise level at each location to be noted on a special chart. By 1944, every operating Pacific submarine had such an installation; during a patrol the records would show which units were becoming noisy and what elements of duplicate machinery should be used in critical situations. By 1945, a fifth hydrophone was installed near the propellers and was connected to a cavitation indicator (CI) addition to the NLM box that flashed a red light whenever the propellers started to cavitate. On most ships this light was mounted in the maneuvering room or conning tower so that by quick control of propeller speed cavitation noise could be avoided.

Passive Listening Capability—1941[35]

At the time of our entry into World War II, U.S. submarines were capable of listening in the ultrasonic range only; i.e., below 25,000 cycles per second. This condition was brought about because in the 1930's NRL attempted to incorporate into one equipment both the active and passive sound system needs for submarines—the JK/QC gear. Since the sound head with a magnetostriction transducer on one side, and a piston-shaped rochelle-salt hydrophone on the other, had to fit into a small bottomside dome, the size-limited hydrophone had to utilize high-frequency listening in order to achieve suitable directivity. At the receiver the signals (generally of cavitating propellers) were amplified in a band centered near 25,000 cps and heterodyned for ear listening to a band centered at 800 cps. The JK was capable of providing detection and accurate bearings for targets proceeding with cavitating screws. However, the following deficiencies were also noted:

[33] Subsurface Warfare, Op. Cit., NDRC Division 6, Vol. 1, pp. 203-204.
[34] Project NS-212-Noise Reduction on Submarines—A Summation of Progress—Office of Research and Invention (formerly the Coordinator of Research and Development), Navy Department (1946).
[35] Directory of Sonar Equipment, BUSHIPS NAVSHIPS 94200.3 (1962).

• Poor classification. The characteristics of the signal that made it possible for a sound operator to recognize particular targets at long range were largely in the sonic band. The JK did not receive these signals.

• Inability to hear slow moving targets. When surface vessels operated at speeds below propeller cavitation, the submarine could not detect their presence.

• Range limitation. The high-frequency signals were attenuated more rapidly so that sonic signals could be received at greater ranges.

• Poor location. On most submarines the equipment was mounted bottomside where its use was impossible when the boat was lying on the bottom.

JP and JT Systems[36]

The New London Laboratory starting in 1941 developed line magnetostriction hydrophones of rugged and simple construction; they possessed good wide-band frequency response characteristics together with adequate directionality. A typical unit was mounted topside, forward on the port side in an arrangement shown in Fig. 24. The hydrophone, in a streamlined baffle, was mechanically trained. In the JP system the hydrophone was 3 ft long; in the JT (shown in Fig. 24) the length was extended to 5 ft. The hydrophone-amplifier system was capable of receiving signals as high as 65,000 cycles per second. A block diagram of typical electronic arrangements is shown in Fig. 25.

Figure 26 shows the units of a JT installation. In the JT modification the hydrophone was divided into two symmetrical sections so that the right-left indicator, designated the RLI (a variety of the bearing deviation indicator, the BDI, developed for active sonar) provided the operator the information of whether the hydrophone was trained on target or required right or left training.

Triangulation-Listening-Ranging (TLR)[37]

In order to execute a successful torpedo attack, it is necessary for a submarine to have accurate information concerning the enemy vessel's course and speed. Determination of these two factors required the use of periscope or radar observation with a final check of range by means of a single ping from the echo ranging gear. Since American practice required closing to attack within 3,000 yd of the target, the necessity not to alert the target often deprived the submarine's attack team of range information during the vital closing phase of attack. The need led to the development of the triangulation-listening-ranging (TLR) systems. It consisted of two JT-type hydrophones, one located near the bow and the other near the stern. The separation of about 240 ft allowed target bearings to be converted to range by triangulation. This system was capable of passive ranging within about 10 percent out to 3,000 yd for targets within 50 deg of the beam. This accuracy was better than that usually obtained by periscope. The components of the TLR system are shown in Fig. 27.

Noisemakers and Decoys

When prosubmarine warfare received increased emphasis in 1943, one of the first programs requested by submarine commanders in the Pacific area was one directed to neutralizing or misdirecting enemy detection methods. The San Diego Laboratory and the Massachusetts Institute of Technology Laboratory were especially involved in this effort. The former had acquired a great deal of applicable experience in developing training devices for antisubmarine personnel; the latter had participated in the development of mechanical noisemakers for sweeping acoustic mines. Both groups were experienced in

[36] Subsurface Warfare, Op. Cit., NDRC Division 6, Volume 1, pp. 203-204.
[37] Summary Tech Report NDRC Op. Cit., Chap. 12.

Fig. 24. JT Hydrophone (figure reproduced from Ref. 37)

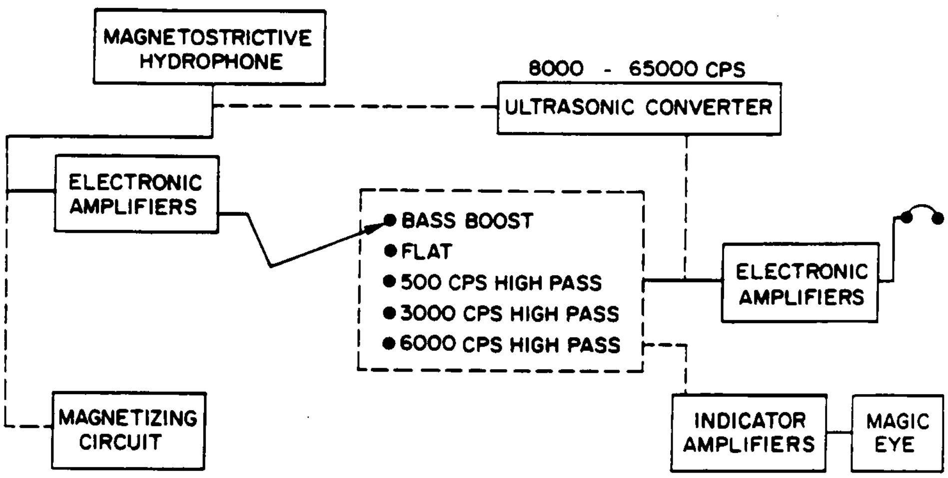


Fig. 25. Block diagram of typical JP/JT Circuits

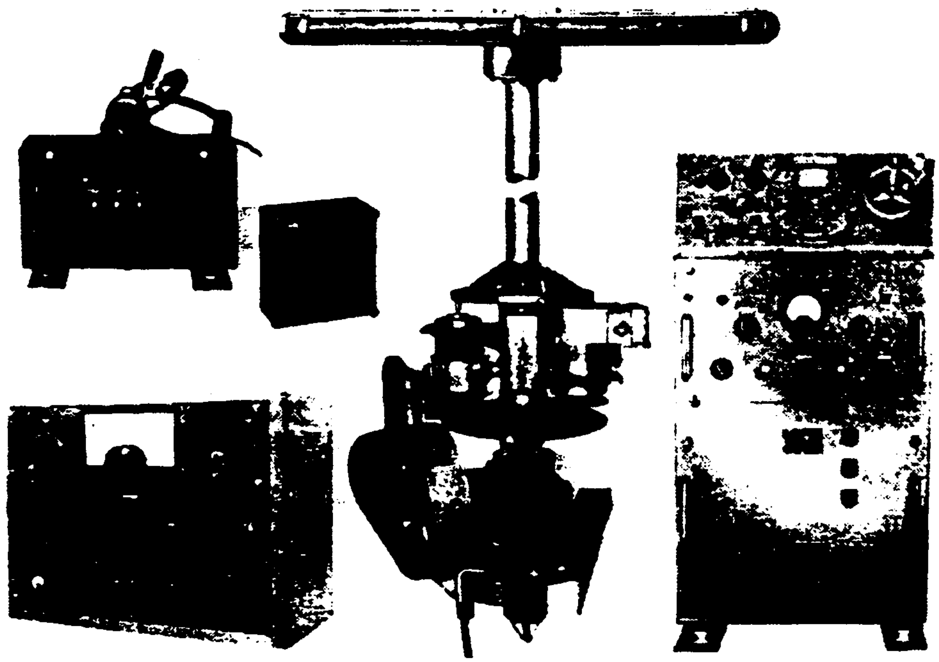


Fig. 26. Elements of Installation (figure reproduced from Ref. 37)

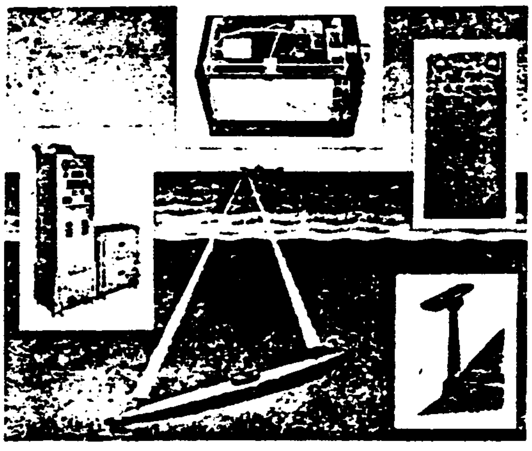


Fig. 27. Components of the TLR System (figure reproduced from Ref. 37)

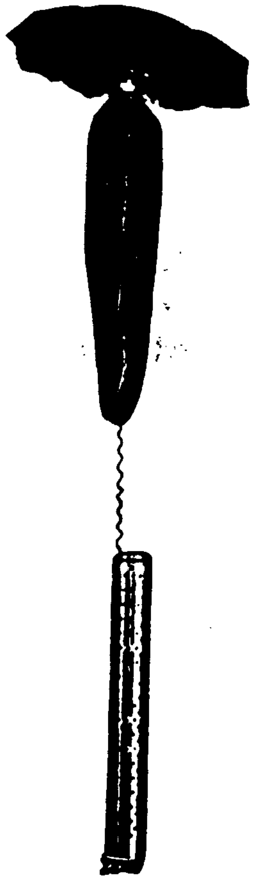


Fig. 28. Mark 20 pepper signal supported on depth control (figure reproduced from Ref. 37)

the measurement and analysis of ship sounds which were to be masked or simulated. An effective noisemaker for shallow water applications was the Mk 20 "pepper signal" shown in Fig. 28. Small explosive charges housed in a tube were periodically released to keep the reverberation level high in the area of operation. A more sophisticated submarine simulator-decoy is shown in Fig. 29. Table V lists representative noisemakers and decoys developed during 1943-1945.

Anechoic Coatings[38]

Both the German Navy and the American Navy had programs to decrease the ability of active sonars to detect and locate submerged submarines. The German "Alberich" consisted of a rubber layer with air-filled voids cemented to the outside of U-boats and the American version, worked on by the Massachusetts Institute of Technology, used air-entrained in latex paints. The German coating was installed experimentally on a number of U-boats, the American coating received very limited experimental use.

Both coatings experienced problems of adhesion and the loss of effectiveness with successive dives of the submarines. The cycle of surface-submergence at times resulted in the loss of entrained air and the subsequent loss of coating effectiveness. The Alberich coating applied to the German submarine Type XXI-C was the most successful in solving problems related to depth. However, adhesion almost solved for slow moving U-boats, continued to be a problem because of the much higher submerged speed capability of the XXI—i.e., to 18 knots.

[38]W. Kuhl, et al., "Sound Absorption and Sound Absorbers in Water," BuShips publication 900164 (June 1947).

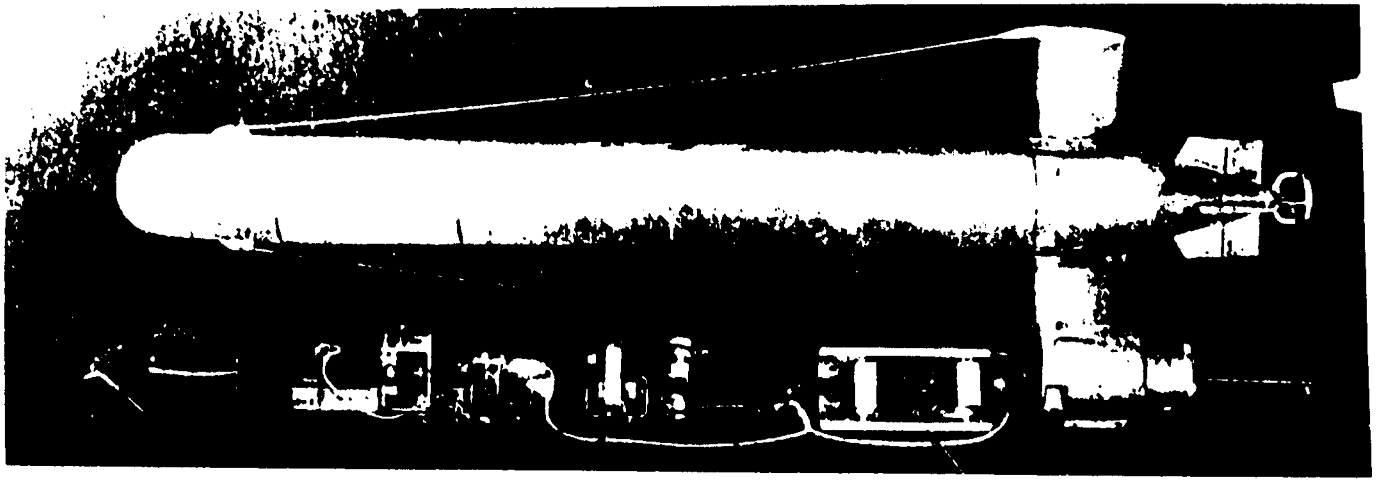


Fig. 29. NAD-6 sound beacon assembly and subassemblies (figure reproduced from Ref. 37)

TABLE V
Representative Noise Makers and Decoys Developed During 1943 to 1945

Type	Purpose	Description
NAC Sound Beacon	Jam enemy echo ranging	A swept range of signals used in echo ranging were radiated with high intensity device released through signal ejector tube hovered at 50 ft.
NAH Sound Beam	Jam enemy echo ranging	As above but radiated jamming signals tuned to enemy echo-ranging frequency.
Pepper System	Jam enemy passive listening systems, especially in shallow water	A series of small explosive charges were released in sequence to explode at a firing rate of two shots a second. Reverberations maintained a masking level of noise between explosions. Unit released through signal tube.
NAD Sound Beacon	To provide a mobile false target for enemy sonar	Self-propelled decoy released from torpedo tube: simulated sub noise and returned echoes to energy sonar with levels equivalent in strength to full-size submarine.

CONCLUDING REMARKS

America was doubly fortunate during World War II: Axis errors allowed her time to recover from initial hard blows; and superb leaders emerged to enable the Nation to make the best use of the time granted. The organization and participation of the scientific community played a large part in winning the war. In the area of undersea warfare, a salient feature was the partnership of the Navy and the civilian scientists. In the area of research and development the Navy was advisory to the civilian-led effort; in the area of operations, the civilians were advisory to the Navy as to the best use of available resources.

Under Division 6 of the National Defense Research Committee were organized all the elements concerned with the detection, identification, *localization and kill* of enemy submarines and surface vessels. It is striking that during the war "underwater acoustics" emerged as a greatly enlarged field, both in areas of investigation and in the numbers of investigations involved. Torpedo and submarine silencing efforts were initiated, sound propagation studies for tactical application were extended, and both active and passive sonars were incorporated into systems for weapon delivery or enemy weapon avoidance.

In reading the history of the times, one is impressed by the close cooperation of acousticians in the weapon areas and with those involved with submarine and ship platforms. The Bureau of Ordnance requirements for weapons and the Bureau of Ships requirements for sonar systems were coordinated by the common scientific manpower of Division 6. Commonality of effort existed in the weapon- and ship-silencing areas as well as in the problems of hull-mounted weapons and acoustic homing of weapons. In addition to "burrowing into all corners of the underwater acoustics problem," acousticians became involved with the problems of men in the man-machine loop, especially the sonar operator—his ears, his eyes, and his decision making process. Criteria were sought to enable electrical circuits in weapons to duplicate in part the logic of operator decision making. Experience in operator training was translated (oft times by the same individuals involved) into weapon system countermeasures. *In many ways, underwater acoustics of the war period was more integrated than at present.*

Vannevar Bush, who helped organize the war effort, emphasized that the research and development community required organizational independence of military control. When the war was over, the Navy attempted to continue the wartime partnership with the scientific community; the success of the effort was dependent on strong civilian as well as strong Navy officer leadership.

The partnership could not relax with the coming of "peace." Like preceding wars before it, World War II bequeathed to its survivors more problems than it settled. Even before the hot war terminated, a cold war started between the Democracies and the USSR. Soviet Russia after the fall of Germany raced the United States and the United Kingdom to gather German war booty concerning advanced submarine design and construction. The Soviets gathered all German personnel, material and equipment that could be used to build up a future submarine fleet. The United States and United Kindgom efforts in Undersea Warfare could not therefore be disbanded.

The advent of the "cold war" continued the relationship between the civilian scientific community and the Navy, but in a different framework. One of the new organizations established for this purpose was the Office of Naval Research. The OSRD/NDRC laboratories were either disbanded or transferred to naval management. The history to follow will discuss the postwar political, technical and administrative problems that related to undersea warfare acoustics.

ACKNOWLEDGMENT

The author would like to acknowledge the assistance of Dr. John Bouyoucos who kindly furnished transcripts of tape recordings of the reminiscences of Dr. F. V. Hunt who headed the Harvard Underwater Sound Laboratory during World War II. This material covering the World War II time interval provided guidance to the author as to what information to include in this survey.

This article was prepared under contract No. N 00014-74-C-0210 with the Office of Naval Research.